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Modelling tree density effects on provisioning ecosystem services in Europe

Josep CROUS-DURAN[1], Anil R. GRAVES[2], Joana A. PAULO[1], Jaconette MIRCK[3], Tânia S. OLIVEIRA[1], Sonja KAY[4], Silvestre GARCÍA DE JALÓN[2], João H.N. PALMA[1]

[1] Forest Research Centre, School of Agriculture, University of Lisbon, Tapada da Ajuda, 1349-017 Lisboa, Portugal

[2] Cranfield University, Cranfield, Bedfordshire, MK43 0AL, UK.

[3] Department of Soil Protection and Recultivation, Brandenburg University of Technology Cottbus – Senftenberg, Germany

[4] Agroscope, Zurich, Switzerland

Corresponding author*: jcrous@isa.ulisboa.pt

Abstract

Agroforestry systems, in which trees are integrated in arable or pasture land, can be used to enable sustainable food, material, and energy production (i.e. provide provisioning ecosystem services) whilst reducing the negative environmental impacts associated with farming. However, one constraint on the uptake of agroforestry in Europe is a lack of knowledge on how specific agroforestry designs affect productivity. A process-based biophysical model, called Yield-SAFE, was used: 1) to quantify the food, material and biomass energy production of four contrasting case study systems in Europe in a common energy unit (MJ ha^{-1}), and 2) to quantify how tree density determined the supply of provisioning ecosystem services. The Yield-SAFE model was calibrated so that simulated tree and crop growth fitted observed growth data for reference monoculture forestry, pasture, and arable systems. The modelled results showed that including trees in pasture or arable systems increased the overall accumulated energy of the system in comparison with monoculture forestry, pasture, and arable systems, but that the accumulated energy per tree was reduced as tree density increased. The greatest accumulated energy occurred in the highest tree density agroforestry system at all the case study sites. This suggests that the use of environmental resources, such as light and water, for obtaining provisioning services is most effective in high density agroforestry systems. Further modelling should include tree canopy effects on micro-climatic and the impact this has on pasture, crop, and livestock yields, as well as the impact of tree density on the economic value and management of the different systems.

Keywords

Yield-SAFE, agroforestry systems, montado, dehesa short rotation coppice, silvoarable, silvopasture.

Introduction

Global population growth, combined with rising levels of consumption, are increasing the demand for natural resources and pressure on the environment. In this context, agroforestry systems, where trees are integrated in arable or pasture land, have received considerable attention in both tropical (Garrity et al. 2010) and temperate regions (Palma et al. 2007). They are increasingly seen as a promising approach for improving food, energy, and material provision (Glover et al. 2012) along with environmental conservation and stimulation of local economies (IAASTD 2009). The components of agroforestry systems can be complementary in their use of solar radiation and water, leading to an overall higher biomass production than when the same components are grown in separate tree, pasture, or arable systems (Graves et al. 2007). Rivest et al. (2013) also suggested that tree presence has a major role to play in landscapes, acting as a keystone structure for maintaining ecosystem services. However, Torralba et al. (2016) reported in a literature meta-analysis that no clear effect of agroforestry on provisioning services could be determined, partly because of the different ways in which provisioning services can be defined e.g. crop production or combined crop and tree production. Smith et al. (2013) reported a reduction of arable crop yields in agroforestry systems when physical resources such as light in temperate regions (Chirko et al. 1996; Reynolds et al. 2007; Benavides et al. 2009) or water in the Mediterranean basin (Jose et al. 2004) were limiting. However, the advantages and disadvantages of agroforestry are dependent on site-specific responses by trees, crops, and other components of the system, with large variation between locations and farming contexts (Coe et al. 2014). There is a complex relationship between climate, soil water content, water uptake by trees and crops, plant growth and evaporation, which challenges our understanding of water, radiation and growth dynamics in agroforestry systems. This uncertainty relating to the potential productivity of agroforestry has been suggested as one of the main causes for the low implementation of new agroforestry systems (Pisanelli et al. 2014).

The use of models can help develop knowledge on how different components of an agroforestry system interact in space and time. Furthermore, process-based models can be used to analyse management decisions in uncertain climatic conditions (Cuddington et al. 2013). The Yield-SAFE model is a process-based growth model that evaluates competition between trees and crops for water and light (van der Werf et al. 2007) which has been extensively used to predict tree and crop yields in arable, agroforestry and forestry systems. Within the AGFORWARD project (Burgess et al. 2015) Yield-SAFE was calibrated for several new agroforestry systems in Europe and improved with new algorithms to predict the output of additional provisioning ecosystem services such as pasture, root crops and tree fruit production (Palma et al. 2016).

The objectives of this study were: 1) to quantify in energy units (e.g. MJ ha^{-1}) the food, material and biomass energy production of four contrasting case study agroforestry systems in Europe, and 2) to improve understanding of how tree density determines the supply of provisioning ecosystem services. The Yield-SAFE model was used on four sites in different parts of Europe and for each site, six different land use alternatives of differing tree densities were considered: a crop rotation or pasture (zero tree density); four agroforestry systems (intermediate tree densities) and a tree-only system (high tree density).

Materials & Methods

Several steps are needed for the use of the Yield-SAFE model. These include: 1) the identification and description of the crop, pasture, agroforestry and tree-only systems to be analysed; 2) the collection of site data on weather, soil texture and depth, and management practices for the crops, pasture, livestock and trees; 3) the identification, often from literature, of parameter values for the crops, pasture, livestock and trees for the calibration of the model, and; 4) calibration of the model outputs against field data. The full details of this process are provided in Graves et al., (2007).

For this study, the simulation period was 80 years for all the case study systems. The provisioning ecosystem services were classified according to their origin (tree, crop and livestock) and their use (food, energy or materials) and converted into energy units (MJ ha^{-1}) using the Utilisable Metabolizable Energy value (UME in MJ kg^{-1}) for food products and the gross calorific value (GCV in MJ kg^{-1}) for energy and materials. The use of an energy unit (MJ ha^{-1}) allowed for standardization of provisioning ecosystem services outputs, thereby allowing comparison of the total food, material, and energy produced by the different systems during the simulation period, so that the effects of the different tree densities could be assessed.

Identification and description of the case study systems and their provisioning ecosystem services

Four different types of agroforestry systems were selected to represent different environmental conditions across Europe. These systems were: 1) Iberian wood pastures (dehesas in Spain and montados in Portugal); 2) cherry tree pastures in Switzerland (Swiss orchards); 3) poplar silvoarable systems in the United Kingdom, and; 4) short rotation poplar coppice systems for biomass energy production in Germany. The meteorology, soil conditions, and the agroforestry components for each system are described in Table 1.

Insert Table 1

To assess how tree densities affected the supply of provisioning ecosystem services, six tree densities were analysed for each site. These included: 1) conventional agriculture with no trees (pasture-only or arable crop-only); 2) four agroforestry alternatives of different tree densities (labelled AF1, AF2, AF3 and AF4); and 3) tree-only systems with no crop or pasture production. The tree-only systems were developed assuming standard management practice for tree plantations at the locations assessed, and typically were established at a relatively high tree density, which was reduced over time using a thinning regime. The agroforestry alternatives were assumed to maintain the initial tree density throughout the simulation period (Table 2).

Insert Table 2

Iberian wood pastures

According to den Herder et al. (2017), the montado and dehesa systems in Portugal and Spain cover about 3.5 – 4.0 million hectares. The systems are characterized by low trees densities (20 to 50 trees ha^{-1}) combined with arable and/or pastoral activities. Depending on the main tree species present, two main different types of montados can be found: 1) Cork oak montado where *Quercus suber* L. trees and cork extraction is the main economic activity, and 2) Holm oak montado where *Quercus rotundifolia* L. are the dominant tree species, and the main economic activity is animal husbandry (cattle for beef production and/or Iberian pigs and also sheep/goat for meat, and milk derivates) under extensive practices. For this modelling assessment, the montado system was defined as a pure holm oak plantation, providing acorns between September and January, and grass during the entire year for grazing livestock. For the forestry system, typical thinning regimes were used. Livestock were absent but acorns were considered to be available as fruit from the trees. Regular pruning of the trees, removing 10% of the total biomass, was assumed to occur every 12 years to increase the light reaching the pasture (Olea and Miguel-Ayanz 2006). Provisioning ecosystem services provided by the system included food in the form of meat from the livestock, and energy from the trees in the form of firewood derived from tree pruning and thinning. The livestock were considered to feed on pasture and acorns, when these were present.

Cherry orchards in Switzerland

Cherry tree orchards are traditional agroforestry systems that are widely spread throughout central Europe, and particularly in Switzerland (Sereke et al. 2015). These systems consist of tall, mixed fruit tree species, combined with grass or crops. Tree densities vary between 20 to 100 trees ha^{-1}, and the most common fruit tree species are apple (*Malus* spp.), pear (*Pyrus* spp.), plum (*Prunus domestica*), and cherry trees (*Prunus avium*). These species were primarily planted to provide fruit but they also provide timber and nowadays the most common use of the wood is for firewood. The grass understorey was traditionally meadow or pasture for feeding animals. Despite a steady decline over recent years, these systems currently cover around 41,000 ha of agricultural land in Switzerland (Herzog 1998).

In this modelling assessment, the system was assumed to provide cherries during summer (June-July) and grass as fodder for cattle or sheep for the whole year. Pruning was assumed to occur every third year, and a one percent removal of the total biomass was also assumed to ensure constant fruit production. Timber was assumed to be used in furniture and was obtained in year 80 with the final harvest of the trees. For the agroforestry alternatives, it was considered that the management of the trees was for fruit production, whilst for the forestry system, the management was for timber production. The provisioning ecosystem services provided by cherry tree pastures thus included food in the form of cherries and grass for livestock grazing the pasture, material in the form of timber, and energy from wood for heating.

Silvoarable systems in the UK

In 1992, a network of experimental silvoarable systems was planted in the UK where rows of poplar trees (*Populus* spp) were planted with arable crops in alleys. As part of this, hybrid poplar for timber was planted in Silsoe (Bedfordshire, UK) in forestry and agroforestry schemes with cereal rotations including wheat (*Triticum* spp) and barley (*Hordeum vulgare*). Arable control treatments were managed in the same way as the cereal intercrop and trees were planted at a tree density of 156 trees ha^{-1} with rows oriented in a north-south direction (Burgess et al. 2005).

Here, the combination of poplar trees for timber and cereal intercrops supplied food in the form of grain and material in the form of timber and cereal straw. The simulation period was 80 years and consisted of four poplar rotations of 20 years each. During tree growth, material from formation pruning was assumed to be discarded and was therefore not included in the analysis. In the agroforestry scenarios, tree density was increased, by reducing the distance between trees in the tree line so that the crop area remained constant at 80% of the total area.

Short rotation coppice in Germany

Short-rotation coppice (SRC) with poplar or other fast-growing species for the production of bioenergy is gaining interest as a possible means of decarbonising energy supplies. In temperate zones these systems can be used to produce biomass feedstocks, providing one approach to meeting increasing demand for self-sufficient energy supplies in decentralized rural areas (Gruenewald et al. 2007).

An agroforestry alley cropping trial was established in Forst (Lausitz, north-eastern Germany) in 2010 and 2011. The system included 11 m wide hedgerows with crop alleys ranging from 24 m to 96 m in width. The tree hedgerows included two poplar varieties, Max 1 (*Populus nigra* × *Poplar maximowiczii*) and Fritzi-Pauley (*Poplar trichocarpa*), and black locust (*Robinia pseudoacacia* L.). The trial area occupied around 40 hectares and tree densities in the tree rows were between 8,715 trees ha^{-1} and 9,804 trees ha^{-1} depending on whether a single or double row design was used.

Here, the modelling work assessed an alley cropping system with poplar Max 1 variety (*Populus nigra* × *Poplar maximowiczii*) SRC as the tree hedgerow, and winter wheat (*Triticum durum)* followed by sugar-beet, as the crop rotation. Tree coppicing was assumed to occur every four years, resulting in 20 rotations over the 80-year time horizon, and the trees were assumed to be replanted every five rotations. Due to the width of the tree strips in these systems, it was assumed that the two double rows located in the middle would behave like pure SRC, whilst the two double rows located on the edge of the tree strip would interact with the crop (Salkanovic, 2017). The provisioning ecosystem services includes the supply of food from cereal grain and sugar-beet, material from wheat straw, and the energy provided by the tree component.

Methodological approach for provisioning ecosystem services estimation

Yield-SAFE was used to predict the quantity of food, material, and energy provided by the trees, pasture, and crops for human and livestock consumption. Yield-SAFE was selected for this study for two reasons. Firstly, because it can model water and light capture and competition between tree and crop/pasture components in agroforestry systems, and secondly, because it can also simulate pure crop-only and pasture-only systems as well as tree-only systems, so that comparisons between the different land uses can be made.

For the calibration, a default set of parameters for the “potential” monoculture yields of trees, crops and pasture species was developed assuming no water limitation on growth yields (see details in Graves et al., 2007 for full explanation). The model was then calibrated for site specific “reference” monoculture yields of the trees, crops, and pasture species. For this, crop and tree calibration data were taken from a variety of sources including Cubera et al (2009) and Oliveira et al (2018) for pasture and holm oak in Portugal, Graves et al. (2010) for crops and poplar yields in the UK, Palma et al (2017b) and Sereke et al (2015) for pasture and cherry tree yields in Switzerland, and Mirck (2016) for crop and poplar SRC in Germany (see Figure 1).

Weather data (daily solar radiation, temperature, and rainfall) were then extracted for use in Yield-SAFE from the CliPick tool (Palma et al 2017a) while information relating to soil texture and depth was provided by field data from the case study sites. Then selected parameters in Yield-SAFE (the water use efficiency, harvest index, and light use efficiency) were used to determine water limited reference yields for tree and crop species by adjusting these parameters within the ranges found in the literature so that estimated yields from Yield-SAFE matched the reference yields (see Graves et al., 2007 for full explanation).

Food production for human and livestock consumption was predicted by Yield-SAFE for fruit using tree canopy cover and leaf area index (LAI), for crops using the grain or root yield, and for pasture using the total pasture yield less 10% that was assumed to be left in the field after grazing. A livestock carrying capacity was quantified using data on the available UME of food (grass and/or acorns) consumed by the livestock and the livestock unit energy requirement (LUER: 103.2 MJ d^{-1}) as proposed by Hodgson (1990).

Raw materials were assumed to be outputs that would be used for on-farm construction or saleable products such as timber, bark, or wool. In this study, it was assumed that poplars from the UK, and cherry trees in Switzerland provided timber, estimated using the cumulative above ground biomass in year 80. For the montado system, energy from the standing trees was included to complete the energy balance of the system, even though these trees would not normally be felled during an 80-year time horizon. Cereal straw was also considered to be a material.

Energy was assumed to be produced either directly as the main output of the system (e.g. dedicated bioenergy plantations) or, indirectly as a by-product (e.g. pruning or thinning) from the tree component. For the alley cropping SRC system in Germany, energy production was viewed as the main output, and the management of the system was assumed to maximize wood supply for local combined heat and power plants. For the montado system in Portugal, cherry orchard system in Switzerland, and poplar system in the UK, energy production was viewed as the consequence of management operations related to other objectives of the system, such as food or timber production, which nevertheless, provided an important resource for cooking and heating for local people.

Results and discussion

Modelled tree, crop, and pasture yields

The modelled yields of the crop-only or pasture-only systems for the simulation period were made to match observed reference values for each location and modelled variations in yields between years were due to differences in annual weather data, but were within the yield ranges reported for each case study area (Figure 1). The timber yields for trees were then compared with tree growth data derived for widely spaced oak trees

(20 and 50 trees ha^{-1}) in montados in Portugal, cherry and poplar forests in Switzerland and the UK, and SRC agroforestry systems in Germany (Figure 1).

Insert Figure 1

Under montado, at a density of 50 trees ha^{-1}, the simulated trees reached a height of 7 m, a diameter at breast height (DBH) of 40 cm, and an above-ground biomass of 570 kg, in year 80. These results seem reasonable as observed trees of the same age, range between 500 - 600 kg in above-ground biomass, 30-40 cm in DBH, and 5.5 - 8.0 m in height (Oliveira et al. 2018). For the understorey component, the mean yield predicted by Yield-SAFE for monoculture pasture was 2.3 Mg ha^{-1} yr^{-1}. This value is within the range of 2.0 – 4.0 Mg ha^{-1} yr^{-1} reported in Cubera et al. (2009).

In Switzerland, timber production results from Yield-SAFE were similar to published data. For year 60, Yield-SAFE estimated a timber volume of 1.4 m^3 $tree^{-1}$ and 0.99 m^3 $tree^{-1}$ respectively for 40 trees ha^{-1} in the agroforestry system and for the tree-only system. These results are in accordance with Sereke et al. (2015) who for year 60 reported timber volumes of 1.34 m^3 $tree^{-1}$, 1.14 m^3 $tree^{-1}$, and 1.07 m^3 $tree^{-1}$ respectively, for two wild cherry timber in Switzerland at 40 and 70 trees ha^{-1} (both agroforestry systems), and a forestry system, with an establishment density of 816 trees ha^{-1}, thinned to a final density of 100 trees ha^{-1} in year 60.

For the silvoarable system in the UK, simulation results using Yield-SAFE were coherent with the results obtained at experimental sites in the UK. Graves et al (2010) reported yields for winter wheat, barley, and oilseed rape of 8.23 Mg ha^{-1}, 6.83 Mg ha^{-1} and 3.44 Mg ha^{-1} respectively. The simulated results for the initial years of the agroforestry system achieved similar results on a per hectare crop basis for winter wheat, barley, and oilseed of 8.30 Mg ha^{-1}, 6.92 Mg ha^{-1} and 3.30 Mg ha^{-1} respectively. But these declined as the trees started to grow. Graves et al. (2010) used timber volumes per tree of 0.35 and 2.41 m^3 in year 12 and 30 respectively to calibrate Yield-SAFE for the forestry reference system. Here, simulations over a 30-year time horizon predicted timber yields of 1.9 m^3 $tree^{-1}$ and 2.7 m^3 $tree^{-1}$ for the forestry and for the agroforestry alternative (156 trees ha^{-1}) respectively.

In Germany arable monoculture simulations using Yield-SAFE provided similar crop yields (4.0 - 4.5 Mg ha^{-1} for winter wheat and 16.52 Mg ha^{-1} for sugar beet) to the results obtained for the Forst site control plot (4.9 Mg ha^{-1} and 16.1 Mg ha^{-1} respectively). The tree biomass results from Yield-SAFE (3.56 kg $tree^{-1}$) were similar to those reported by Mirck (2016) after four years for a stand density starting at 8,497 trees ha^{-1} and finishing at 6,295 tree ha^{-1} to give a total stand biomass yield of 22.6 Mg ha^{-1} (3.59 kg $tree^{-1}$).

Predicted supply of provisioning ecosystem services

The systems showed substantial differences in the energy accumulated over the simulation period (Figure 2). There was a large difference between the montado that was only able to accumulate between 2.8 and 4.8 million MJ ha^{-1} over 80 years and the silvoarable systems in the UK which accumulated between 12 and 17 million MJ ha^{-1} over 80 years. Between these extremes, the Swiss cherry tree systems and the SRC systems in Germany were able to accumulate between 5 and 10 million MJ ha^{-1} and 10 and 14 million MJ ha^{-1} over 80 years respectively. These results were largely explained by: 1) differences in weather and soil conditions between the four biogeographical regions that influenced the potential biomass growth of the systems, and 2) differences in the light and water use efficiency of the tree and crop elements that formed each system.

Insert Figure 2

The montado is an extensive silvopastoral system where livestock feed mainly on pasture, and acorns provide additional energy. Modelling results suggested that there was a decrease in food for livestock as tree canopy area increased over the simulation period (Figure 3). In the agroforestry systems, this decrease in the energy available for livestock food was associated with a reduction in pasture yield due to tree competition for water and light of 12% and 50% in year 80 for the 50 and 200 trees ha^{-1} densities respectively, which was not compensated for by the availability of acorns. In the forestry system, the additional energy provided by the thinnings and the acorns also failed to compensate for the loss of the energy that was available in the grass as grass was assumed not to grow in the system. Thus, the overall energy accumulated by the forestry system was lower than that accumulated in the treeless pasture and agroforestry systems (Figure 3).

Insert Figure 3

The modelled results for year 80 showed carrying capacities of 0.9 LU ha^{-1} (93 MJ d^{-1}) and 0.7 LU ha^{-1} (72 MJ d^{-1}) for the agroforestry system at 50 trees ha^{-1} (MONTPT-AF1) and 100 trees ha^{-1} (MONTPT-AF2) respectively (Figure 4). These values were higher than the optimum livestock carrying capacity of 0.18 - 0.60 LU ha^{-1} (62 MJ d^{-1}) reported by Godinho et al. (2014) for mature montados with a canopy cover of 20 - 50% in southern Portugal. This is because farmers must consider stocking levels in the context of other management factors, for example, the periods of low grass production, and the cost of feed imported to support livestock between grass production peaks (ref). The simulations (Figure 4) suggested that only pure pasture (MONTPT-A) maintained daily energy values above the LUER threshold of 103 MJ d^{-1}. All alternative tree-based systems showed lower food energy availability with the decrease being greater as tree density increased (Figure 3). It is worth noting that during the first 30 years, pasture yields in the agroforestry systems were similar to the yields in the tree-less pasture. During this stage, the impact of the trees in terms of light and water competition was relatively small (Figure 4).

Insert Figure 4

In the Swiss agroforestry systems, the energy accumulation in the fruit production of the trees increased over time and with tree density (Figure 6A) although the rate of energy accumulation levelled off and even declined after year 25. Fruit production was lowest in the forestry system despite the initial high density at planting, because the trees were managed for timber production rather than fruit production. The Swiss forestry system (CTCH-F) showed no energy accumulation in grass (Figure 6B) since there was no predicted grass production. However, in the agroforestry alternatives, the accumulated energy in grass increased as tree density decreased. The energy accumulation in grass was predicted to endure over the whole rotation, although at reduced levels in comparison with the pasture only system (Figure 6B). Whilst the pure pasture (CTCH-A) system maintained energy values at levels that were able to support approximately 1.5 LU ha^{-1} indefinitely, the energy accumulated in the grass of the agroforestry alternative with the lowest tree density (CTCH-AF1) was the only one able to maintain 1.0 LU ha^{-1} until year 80.

Insert Figure 6A and 6B

In the silvoarable systems in the UK, the energy accumulated by the trees compensated for the energy lost as crop production decreased due to the competitive effect of the trees (Figure 7). The greatest energy accumulation occurred in the most densely planted agroforestry system and the lowest in the pasture system. The forestry system (SAFUK-F) despite being planted at a high density and thinned, provided an intermediate level of energy accumulation over the simulation period that was higher than the crop only system, but lower than the all but the most widely spaced agroforestry system.

Insert Figure 7

In Germany, in the agroforestry systems, the hedgerows of poplar SRC increased the total energy accumulated by the system as the crop alley decreased in width (Figure 8). The energy accumulated in the most densely planted agroforestry system was greatest out of all the systems. The crop only system accumulated marginally lower levels of energy than the most widely planted agroforestry system. The forestry system accumulated the lowest quantity of energy out of all the systems.

Insert Figure 8

Tree densisty effects on energy accumulated in provisioning ecosystem services

All the agroforestry systems showed an increase in accumulated energy as tree density increased with the highest tree density system (AF4) (Figure 2) showing the greatest accumulated energy at the four locations. This density was 200 trees ha^{-1}, 104 trees ha^{-1}, 156 trees ha^{-1}, and 24 m alley widths for the Portuguese montado, Swiss cherry tree pastures, UK poplar silvoarable systems and the German SRC respectively. This increase in accumulated energy was relatively small for the montado systems in Portugal and the SRC systems in Germany and relatively large for the poplar silvoarable system in the UK and the Swiss cherry pasture systems. Conversely, the energy accumulated in provisioning ecosystem services was lowest for one of the monoculture systems at each site. This was for the forestry system in Portugal, pasture system in Switzerland, crop system in the UK, and pure SRC system in Germany.

However, the energy accumulated per tree also varied as tree density changed. For all the systems, the energy accumulated per tree was greatest in the AF1 systems which had the lowest tree densities. This was 50 trees ha^{-1}; 26 trees ha^{-1}; 56 trees ha^{-1} and 96 m alley widths for the Portuguese montado, Swiss cherry tree pastures, UK poplar silvoarable systems and the German SRC respectively (Figure 9).

Insert Figure 9

These results align with previous studies that show that an increase in tree density in agroforestry systems produces competition for natural resources such as light, water, and nutrients leading to a reduction of the overall biomass produced per tree (Graves et al., 2007; 2010). Here, this was observed for all the systems analysed. This reduction in individual tree biomass appears to occur even though the tree seeks to compensate for this competition as tree density increases, for example, by improving the capture of water with deeper roots, or the capture of radiation by increasing canopy height or leaf area (Eastham, 1990; Toillon et al 2013).

A key factor in considering the effects of tree density on the accumulated energy in provisioning ecosystem services is in terms of the tree canopy effects on resource availability and how this affects tree, pasture, crop and livestock productivity. Further research is needed to allow Yield-SAFE to account for microclimatic effects. These should include the tree canopy effects on wind, temperature, and vapour pressure deficits (Palma et al 2017b) as observations have shown that productivity in agroforestry systems can also be increased in part due to soil moisture benefits (Cubera et al 2009; Rivest et al 2011; López-Díaz et al 2015). By considering only water and light competition, Yield-SAFE currently omits important benefits of the tree canopy, potentially under predicting the beneficial impacts this may have on livestock and understory pasture and crops. The results presented here may therefore be conservative and the energy accumulated in the provisioning ecosystem services under estimated. For example, in the case of livestock, tree canopies provide shade and shelter from extreme weather conditions, reducing the energy they metabolise for body temperature regulation and increasing the energy available for body weight gain. The effects trees can have on reducing wind speed, temperature, and vapour pressure deficits, conserves soil moisture and potentially extends the growth period for pasture and crops, allowing for greater energy accumulation within the system.

Conclusions

Agroforestry provides an approach for diversifying the supply of provisioning ecosystem services from the same land area whilst at the same time reducing the negative environmental impacts associated with agriculture. This paper provides a process-based understanding of the effects of tree density on four contrasting agroforestry systems in different parts of Europe. Using Yield-SAFE, the effects of different tree densities on the food, material, and energy production in terms of total energy production over an 80-year simulation period were predicted. These showed that adding trees to monoculture arable or pasture systems increased the accumulated energy. The accumulated energy varied from relatively low values in the drought stressed montado of Portugal and temperature-limited tree-pasture systems of Switzerland, to relatively high values in the temperate environments of the UK and Germany, demonstrating the importance of edapho-climatic conditions when assessing agroforestry systems. However, the increase in energy accumulated due to tree presence was not linear, and tree competition for water and solar radiation increased with tree density, reducing the quantity of understory biomass that could be produced, and the energy accumulated per tree.

Although there are limitations in using energy as a common measure, the approach presented here does provide a means of quantifying the production of provisioning ecosystem services across different tree densities and land use systems in different environmental conditions. Further research should incorporate other important effects of tree canopies on understorey crop and pasture growth, such as temperature and wind speed effects, to study how these effects might be used to improve advice on agroforestry systems. The results should also be linked to economic data to determine the profitability and feasibility of producing provisioning ecosystem services through agroforestry systems relative to monoculture systems.

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Crous-Duran, Josep

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